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Natural frequencies measured from ambient vibration response of the arch dam of Mauvoisin

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SUMMARY

The resonance frequencies of the 250-m-high arch dam of Mauvoisin are obtained by way of ambient vibration tests. It is observed that the resonance frequencies initially increase with rising water level and then decrease with a further rise. This is linked to the two competing features of increasing entrained mass of water (reduction of the resonance frequencies) and of dam stiffening due to closing of the vertical construction joints (augmentation of the resonance frequencies). The ambient vibration test results are complemented by those obtained during earthquakes at an array of 12 accelerographs. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: dams; dynamics; resonance frequencies; ambient vibrations

1. INTRODUCTION

The need for measurement of *in situ* dynamic characteristics and response of large structures is regularly brought-up in the structural dynamics and earthquake engineering community, including for dams [1]. Three complementary projects have been initiated to respond to this quest. One deals with the accelerograph instrumentation of dams with view of obtaining and interpreting the *in situ* earthquake response. The accelerograph arrays installed in five Swiss dams encompass 4 to 12 interconnected instruments [2], the array of 12 three-components accelerographs installed at the arch dam of Mauvoisin being in operation since 1993. A second project deals with the forced-vibration response of the 180-m-high arch dam of Emosson with particular attention paid to dam–reservoir interaction [3]. Four measurement campaigns were conducted in 1997 and 1998 at water levels ranging from 101 to 172 m above base. A third project deals with the identification of the influence of varying water level on the resonance frequencies of the

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250-m-high arch dam of Mauvoisin. It has been undertaken in 1995 and 1996 by means of ambient vibration tests. It is reported upon in this communication.

Aside from addressing issues of their own, the projects also cover a wide range of amplitudes of dynamic response that span from 'large to moderate' as may occur during earthquakes (observed by the accelerograph arrays) to 'low' as generated by forced excitations and to 'very low' as occurring under ambient excitations. In the process, experience has been gained on the implementation of three different techniques of gathering of vibrational data. A literature review on vibration tests of large dams covering the period from 1975 to 1995 has also been prepared [4].

2. INVESTIGATION

2.1. *Objectives*

It has long been known that the water contained in a reservoir affects the dynamic response of a dam in a way best reproduced by hydrodynamic frequency-dependent added-mass coefficients [5, 6]. The two controlling phenomenon of entrained mass of incompressible water (commonly termed Westergaard added mass) and of energy dissipation by waves travelling in the upstream direction (in large reservoirs) have been identified [7]. In this project, the low-amplitude resonance frequencies of the dam are sought for various reservoir levels by way of ambient vibration tests.

The merits of ambient vibration testing lie in measurement 'on demand', in the absence of heavy exciting equipment and in the very low amplitudes of excitation and response. The latter is of value because linear behaviour is expected to prevail in dams—at least in sound ones — under such conditions. What are believed to be the low-amplitude linear dynamic characteristics of the structure are thus obtained, the mastering of which both in terms of understanding and of modelling being a prerequisite to addressing the non-linear behaviour that might occur during large earthquakes.

2.2. *Dam of Mauvoisin*

The double-curvature arch dam of Mauvoisin is sketched in Figure 1. It is located in the Swiss Alps at an altitude of 1976 m above sea level (level of crest). It is the fourth highest concrete dam in the world with 250.5 m. It has a crest length of 520 m, a base thickness of 53.5 m, and a crest thickness of 12 m. Built from 1951 to 1957 at a height of 237 m, it was heightened in 1989–1991.

The level of the water in the reservoir normally varies between 74 m above base in the spring (elevation of 1800 m) and 249 m above base in the fall (elevation of 1975 m). The reservoir contains 211 mio. m^3 of water when full for a lake surface of 2.1 km^2. The large variation in reservoir level is an important feature of the project as it permits a clear identification of the influence of the impounded water on the low-amplitude dynamic characteristics of the dam.

3. EXPERIMENTAL SET-UP

3.1. *Test sequences*

The reservoir levels that prevailed in 1995 and 1996 are reported in Figure 2. The periods during which the measurements took place are also indicated.

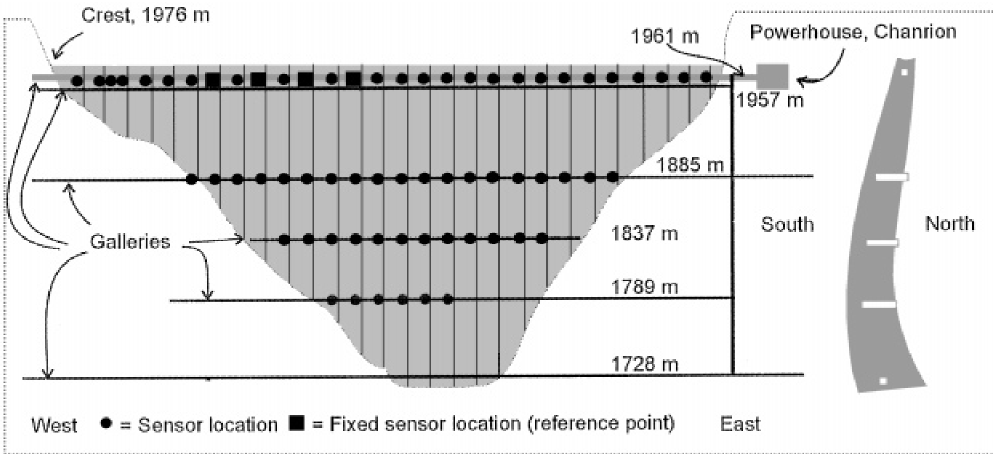

Figure 1. Arch dam of Mauvoisin.

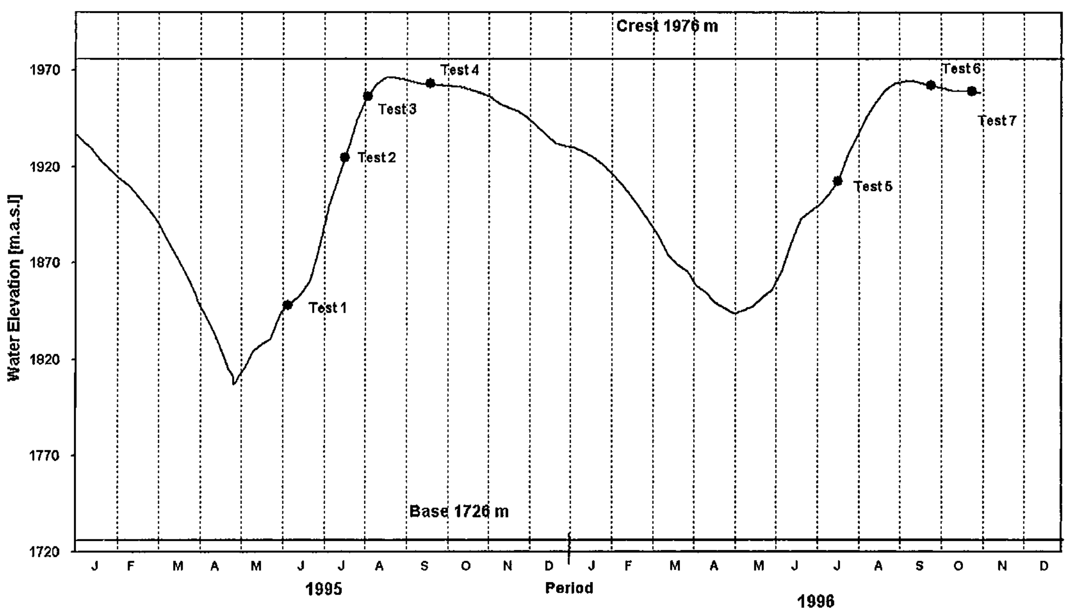

Figure 2. Water elevation in Mauvoisin's reservoir.

The measurements were performed in various configuration details by instrumenting (a) 67 locations of galleries 1961, 1885, 1837 and 1789 (*full configuration*), (b) 29 locations of gallery 1961 (*standard configuration*), (c) 16 locations of gallery 1961 (*limited configuration*) and (d) 1 location of gallery 1957 (*pilot configuration*). The instrumented locations are identified in Figure 1. The test dates and the associated configuration and average water level are reported in Table I.

Table I. Description of the ambient vibration tests.

Test	T1	T2	T3	T4	T5	T6	T7
Date	6–8 June 1995	16–19 July 1995	3–4 August 1995	15–21 September 1995	16–18 July 1996	24–25 September 1996	25 October 1996
Configuration	Standard	Standard	Limited	Full	Standard	Standard	Pilot
Water elevation (m.a.s.l)	1849	1924	1956	1963	1912	1962	1959
Water level above base (m)	124	199	231	238	187	237	234

3.2. Measurement equipment

Up to 8 uniaxial and triaxial force-balanced accelerometers with following characteristics were used simultaneously to record the vibrations of the dam:

Full-scale range:	$\pm$ 0.5 g.
Sensitivity:	5 V/g.
Dynamic range:	130 dB from 0 to 50 Hz, 140 dB from 0 to 10 Hz.
Resonance frequency:	50 Hz.
Damping:	67 per cent of critical.

The analogue signals were amplified by a factor of up to about 2000 using conditioning cards equipped with high- and low-pass filters. Secondary amplifier and filter units were used from test 4 on because very small ambient vibrations had been encountered during some of the previous tests. They provide gains of up to 1000. The signals were subsequently digitized using an external 16-bit analogue-to-digital converter. This system is described further in Reference [8].

3.3. Data analysis

Accelerations of 12 to 109 min duration were recorded with average amplitudes varying from 0.016 μg (T6) to 30 μg (T2). It was however determined that, with the instrumentation at hand, only those records whose amplitudes were of the order of 0.5 μg or more could satisfactorily contribute to the identification of the dynamic characteristics of the dam. The records were processed in time segments of 23 to 205 s.

The resonance frequencies were obtained by inspection of the aggregation of the normalized power spectral density functions of the individual acceleration records (ANPSD, [9]). This was done separately for stream, cross-stream and vertical motions. While this approach may be viewed as a first level ambient vibration analysis, it has the advantage of the easiness of use and is well accepted by the engineering community.

The real (test 1) and complex (tests 2 to 6) modes of vibrations were calculated from the complex-valued transfer functions relating the motion measured at one of the fixed reference locations (identified in Figure 1) to the motions at the remaining locations. They were used primarily to relate the resonance frequencies to one another from one test to the next.

Prerequisite for this procedure of data analysis is that the structural system remains linear and that the modes be well separated and lightly damped [9]. If the structure is further classically

damped, then the modes are real. That not being the case would point to one of the conditions above being not satisfied.

3.4. Treatment of vibrational disturbances

The Chanrion powerhouse is located at the right abutment at crest level, turbinating water from the indirect catchment area before rejecting it into the reservoir. The powerhouse was in operation during part of the tests. A triaxial sensor placed near the turbines permitted the identification of the corresponding excitation frequencies. The corresponding peaks in dam response were discarded during the ANPSD identification.

The Fionnay powerhouse is located 5 km downstream, turbinating the water drawn from the reservoir. It was also in operation during part of the tests. The vibrations induced at the dam—probably due to water vibrating in the penstock—polluted the records to such an extent that those gained during these periods could not be used for identification.

4. RESULTS

4.1. Resonance frequencies from ambient vibration tests

It was attempted to identify 'all' resonance frequencies up to 10 Hz. This appeared not to be possible in all tests for two reasons: (a) an ANPSD peak could not always be correlated with a resonance frequency (due to signal noise, occurrence of close-spaced frequencies, etc.) and (b) not all the modes were sufficiently excited to be identified (still wind conditions, unfavorable wind profile, etc.). Those resonance frequencies which have been identified are reported as dots in Figure 3 as a function of the water level, as well as in Table III. They are entered in parentheses in the table when doubts on the correctness of the identification remain.

The most striking and interesting feature is that the resonance frequencies initially increase with rising water level, and then decrease with a further rise. A rise in water level is associated with

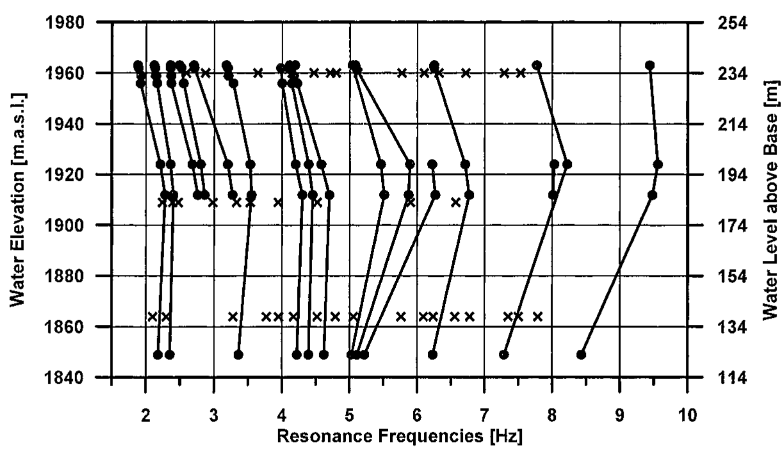

Figure 3. Resonance frequencies as a function of water level.

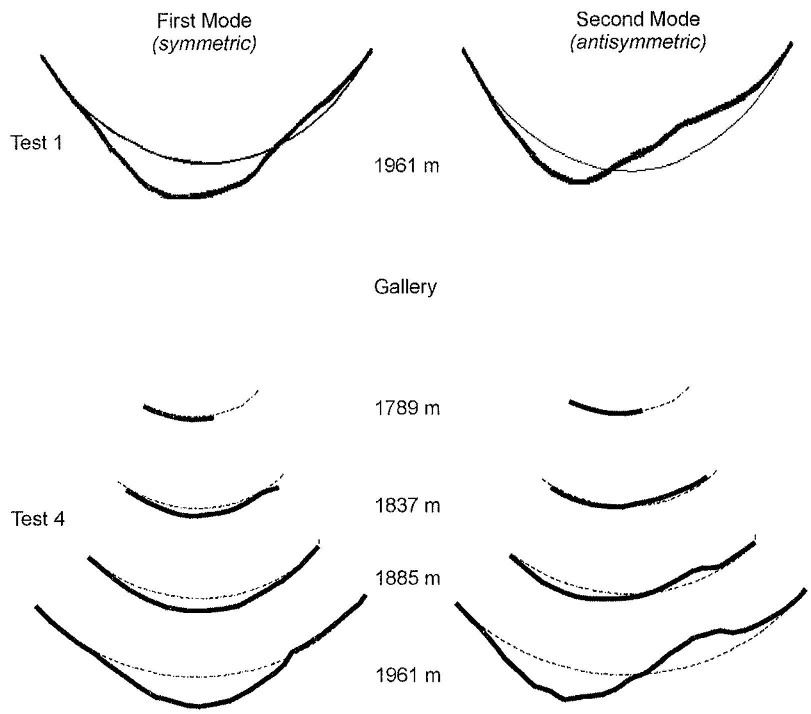

Figure 4. First and second modes determined during tests 1 and 4.

an augmentation of the mass of entrained water. Without the presence of any further effect (as is customarily assumed to be the case in analyses), this would in turn be associated with a monotonic reduction of the resonance frequencies. This not being the case at lower water levels is attributed to the vertical construction joints closing under increasing hydrostatic pressure and thus to the dam becoming stiffer (an effect that is generally not considered in analyses). This latter effect is associated with an augmentation of the resonance frequencies. These two effects compete with one another, the former prevailing at higher water levels and the latter at lower ones.

The variations in concrete temperature that occur in a dam in an alpine region also affect closure of the vertical joints to an extent that might be perceptible in the resonance frequencies. Verification of this hypothesis would require identifying these frequencies in winter.

The real component of the first (symmetric) and second (antisymmetric) modes of vibration are reported in Figure 4 for test 1 (water elevation 1849) and test 4 (water elevation 1963). In the latter test, they have been determined not only at gallery 1961, but also at galleries 1885, 1837 and 1789. The imaginary component of the modes calculated from the data of tests 2 to 6 is small to negligible.

4.2. Resonance frequencies from earthquake records

Three earthquakes that triggered the accelerograph array placed at Mauvoisin have been used in a separate resonance-frequency identification. They are listed in Table II. The peak accelerations

Table II. Earthquakes used for identification of resonance frequencies at Mauvoisin.

Date	1 November 1994	31 March 1996	15 July 1996
Name of quake	Mauvoisin	Valpelline	Meythet
Magnitude Ml	Unknown	4.2	5.2
Focal depth (km)	Unknown	2	5
Epicentral distance (km)	~ 0	13	100
Number of registering stations	9	12	1
Water level above base WL (m)	234	138	183
Note	Possibly explosion or rock fall; three accelerographs disconnected for maintenance reasons.		Only crest station at central section triggered $a_{\max} = 5.3$ cm/s^2 (stream direction)

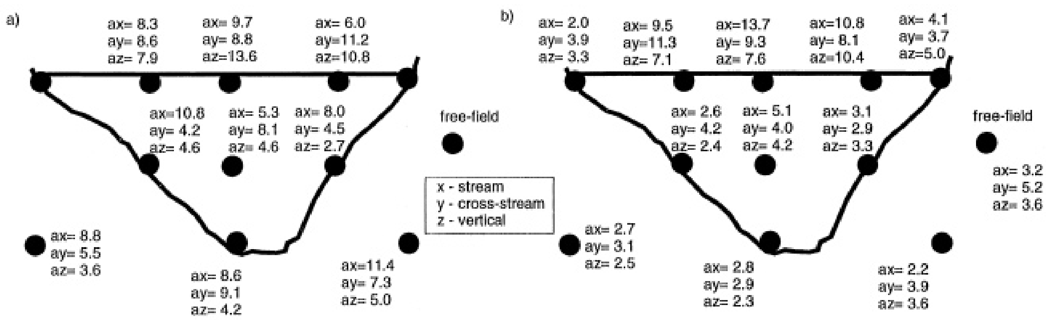

Figure 5. Peak accelerations in cm/s^2 at Mauvoisin: (a) Mauvoisin quake; (b) Valpelline quake.

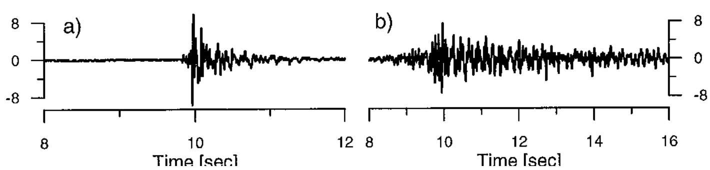

Figure 6. Acceleration time histories in cm/s^2 at Mauvoisin in stream direction (crown station at crest): (a) Mauvoisin quake; (b) Valpelline quake.

recorded during the Mauvoisin and the Valpelline quakes are reported in Figure 5 and selected acceleration time histories in Figure 6 (stream direction of crest station at crown). No amplification of motion is observed in the dam during the local event. Inspection of the records and of the power spectral densities reveals that the motions are of high-frequency content, larger than the resonance frequencies of the dam (it is in fact not certain that the event is an earthquake; although unlikely, an explosion or rock fall near the site is not excluded). On the other hand, an amplification clearly occurs during the Valpelline quake (of up to a factor 5 in the stream direction).

Table III. Resonance frequencies identified at Mauvoisin.

SAP90 WL 124	T1 WL 124	Valpel. WL 138	Meythet WL 183	T5 WL 187	SAP90 WL 199	T2 WL 199	T3 WL 231	Local WL 234	T7 WL 234	T6 WL 237	SAP90 WL 238	T4 WL 238
2.08	2.18	2.10	(2.24)	2.28	2.11	2.21	1.92		1.93	1.89	1.96	1.88
2.36	2.35	2.30	(2.39)	2.40	2.40	2.36	2.16	(2.13)	2.15	2.13	2.24	2.12
			(2.47)									
				2.76		2.68	(2.37)	2.36	2.37	2.36		(2.36)
			(2.98)	2.86		(2.80)	2.55	(2.59)		(2.52)		(2.49)
		3.28	(3.33)	3.27		(3.20)		(2.87)		2.71		(2.70)
3.30	3.36		3.53	3.55	3.34	3.53	3.28	3.20	3.21	3.20	3.14	3.18
		(3.77)	(3.94)									
4.09		3.95			4.00			(3.64)			3.86	
	4.22	(4.17)		4.30		4.20	(4.00)			(3.98)		
4.36	(4.39)	4.52	(4.52)	4.45	4.40	4.39	(4.14)	4.14		(4.09)	4.16	4.11
	(4.62)			4.70		4.58	(4.22)		4.17	4.14		(4.19)
		(4.79)						4.47				
5.56					5.50			(4.71)			5.24	
								(4.80)				
	(5.03)	(5.06)		5.51		5.46						5.04
5.62	5.11		(5.90)	5.87	5.67	5.89		(5.12)		(5.09)	5.38	(5.08)
6.20	(5.22)			6.27	6.17	6.22					5.82	
		(5.76)						5.77				
6.46		(6.09)	(6.57)		6.47			(6.10)			6.07	
7.00	6.23	(6.24)		6.77	7.01	6.71		6.32		(6.25)	6.66	(6.25)
7.12		6.56			7.12			(6.72)			6.77	
7.93		(6.78)			7.95			(7.29)			7.47	
8.09		(7.35)		8.01	8.12	8.03		7.53			7.65	
8.47	7.29	(7.50)			8.51	(8.22)					8.12	(7.77)
9.20		(7.79)			9.23						8.69	
9.88					9.98						9.29	
10.04	8.43			9.48	10.08	9.56					9.63	9.44

The resonance frequencies were identified from the power spectral density functions. They are reported in Table III and in Figure 3 (identified as crosses). The values are again entered in parenthesis when doubts on the correctness of the identification remain. The resonance frequencies that ideally refer to the dam–reservoir system without foundation have also been identified from the transfer functions abutment-dam. They are given in Reference [11], together with those identified at other dams. Calculated natural frequencies (SAP model, [10]) are also reported in the table (identified as SAP90).

A definite correspondence is found between the different sets of values for the first two resonance frequencies as well as for the third resonance frequency according to the SAP model. Additional resonance peaks are however identified in-between (at higher water elevations) and direct correspondence becomes more difficult or impossible for higher frequencies. This is recognized as a weakness in the present study in which more sophisticated calculation models were not used (that would in particular consider water compressibility), nor other technique of system identification.

5. CONCLUDING REMARKS

The tests that were conducted permit the identification of the variation in resonance frequencies with changes in water level. This variation combines the two competing features of increasing entrained mass of water and of closing of the vertical construction joints. The identification of the resonance frequencies is in some instances uncertain, implying that the identification procedure selected is not perfectly suited to dam systems. Others have to be tentatively implemented (e.g. according to Reference [12]). Also, only a few series of tests were conducted. A continuous recording over a full year that would permit to follow more closely the variations in resonance frequencies with the changes in water level and in temperature is needed.

ACKNOWLEDGEMENT

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